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Peak-off-peak load shifting for hybrid power systems based on Power Pinch Analysis

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A B S T R A C T

Electricity load distribution tends to vary throughout the day depending on the time of operations of equipment and processes and the ambient weather conditions. Load shifting from peak to off-peak hours changes the electricity load profile and allows users to control the peak electricity demand and optimise the electricity cost. Power Pinch Analysis (PoPA) has been used recently to guide load shifting aimed at reducing the electricity maximum demand. This work applies the PoPA to optimise the overall electricity cost for a hybrid power system by performing cost-effective load shifting that takes advantage of the peak and off-peak electricity tariffs. Two new heuristics for load shifting have been proposed in this work. The results show that the total outsourced electricity during the peak hours has been successfully distributed to the off-peak hours to minimise the electricity cost.

1. Introduction

Electricity load distribution may vary throughout the day depending on the time of operations of equipment and processes and the ambient weather conditions [1]. Electricity demand of commercial buildings in urban areas during the daytime in the weekdays is much higher as compared to demands during the night time or weekends [2]. The differences of the load profiles and the peak-off-peak electricity tariffs provide facility owners with the incentive to shift part of the peak hours' load to off-peak hours. Load shifting is defined as the process of reallocating the electricity demands from the peak periods when the electricity tariff is high, to off-peak periods when the electricity tariff is low [1]. Load shifting is a form of load management that has been widely applied in the industrial sectors. The total electricity consumption is kept unchanged when performing load shifting. It is an effective way to reduce the peak maximum demand. Shifting the electricity load will minimise the impact of load variation on a system's operation and reduce the electricity cost.

A number of simulation and stochastic optimisation studies have been conducted on load shifting in power systems considering the dynamic pricing of electricity. Pina et al. [3] developed a new energy system model called The Integrated Markal-Eform System (TIMES) to assess the impact of demand side management (DSM) strategies such as dynamic demand response and energy efficiency measures in a hybrid energy generation system. Incorporation of demand dynamics such as load shifting strategies allows an effective capacity factor of the existing as well as the new renewable generators to be installed. Doostizadeh and Ghasemi [4] formulated a day-ahead real-time pricing (DA-RTP) model to determine the optimum real-time prices for consumption behaviour. The proposed pricing model could provide the maximum profit for both the energy provider and consumers via load consumption scheduling in response to the real-time prices. The impacts of time-of-use (TOU) tariffs on electricity demand and load shifting was examined by Torriti [5] using a linear interpolation approach.

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Implementation of the TOU tariffs on residential users allows consumers to pay lower for higher average electricity consumption.

Li and Hong [6] performed load shifting, valley filling and peak clipping using a User-Expected Price (UEP) concept. The new UEP-based home-to-grid demand response algorithm integrates exponential smoothing algorithm and Bayes' theorem. The operation of home appliances can be automatically scheduled by the proposed algorithm, to significantly minimise peak-hour energy consumption and thereby reducing the overall electricity costs. A novel mixed integer linear programming (MILP) model for an integrated biomass and solar system combined with load shifting and energy storage was presented by Hashim et al. [7]. Optimal load shifting and battery storage utilisation can be achieved using the MILP model, in order to obtain storage capacity reduction as well as potential electricity cost saving. Load shifting and energy storage potential was also considered by Azzopardi and Gabriel-Buenaventura [8] for the design of an integrated distributed PV system based on net demand planning (NDP). Results from simulation models show that the impacts of both load shifting and energy storage under NDP can assist in manipulating the timing for PV production or performance for load matching without affecting the maximum PV power delivery.

Göransson et al. [9] applied a linear cost-minimising model known as European Power Dispatch (EPOD) to analyse congestion in the transmission of renewable electricity generation with and without load shifting. Load shifting was found to be an essential factor to be considered during the planning of transmission system expansion. DSM algorithm for peak load reduction considering two non-cooperative games, i.e. the supplier and the customer sides was recently proposed by Jalali and Kazemi [10]. The authors explored the existence and uniqueness of the Nash equilibrium in the two investigated games, in order to maximise the suppliers' profit and customers' daily payoff.

The Pinch Analysis concept for load management in hybrid power systems (HPS) has been presented by Wan Alwi et al. [11]. Power Pinch Analysis (PoPA) was initially developed to establish the minimum targets for outsourced electricity and excess electricity in HPS using graphical [12] and algebraic [13] approaches. The authors later extended and applied PoPA for load shifting in HPS in order to reduce the system's storage capacity and the maximum demand [11]. Ho et al. [14] extended the Electric System Cascade Analysis approach to manipulate the electricity supply and demand in order to reduce the capacity of storage and RE (renewable energy) generators. Application of the insight-based PoPA approaches on load shifting that considers the peak and off-peak electricity pricing for an HPS however has not been presented. In this paper, PoPA is applied to provide insights to formulate a cost-effective load shifting strategy by manipulating the peak-off-peak loads in an HPS. The shifting strategies were developed based on two newly proposed heuristics, with the aim to reduce total outsourced electricity required during peak hours. For each shifting strategy, the electricity cost and the total savings achieved due to the reduced peak hours' outsourced electricity were calculated.

2. Methodology

Prior to the load shifting, the power allocation at each time interval for the original load profile was determined using the graphical PoPA tool called the Outsourced and Storage Electricity Curves – OSEC [11]. The visualisation insights from the OSEC, i.e. the time intervals where outsourced electricity, storage and maximum demand occur provide a useful guideline for the load shifting procedure. Besides, the established targets from OSEC can also assist designers to determine the optimum storage size for their HPS. Table 1 shows the limiting power sources and demands to demonstrate the application of the OSEC for load shifting in an HPS. The Illustrative Case Study is a small scale HPS with three REs, i.e. solar, wind and biomass as the power sources. The system consists of five appliances as the load demands, which were categorised into flexible and fixed (non-flexible) loads. Flexible loads can be operated at any time throughout the day and can be shifted to any time interval, without affecting the service that these appliances provide, e.g. electrical boilers, circulation pumps, and refrigerators [9].

The OSEC was constructed using the Power Composite Curves – PCC [12], by positioning the Source Composite Curve (SCC) directly to the Demand Composite Curve (DCC) within each time interval. Fig. 1 shows the positioning steps in OSEC [11]. If the SCC is more than that of the DCC (SCC slope is less steep than the DCC slope), the excess electricity is available for storage (see Fig. 1a). On the other hand, outsourced electricity would be required if the amount of electricity for the DCC is more than that of the SCC (SCC slope is steeper than the DCC slope) – Fig. 1b.

The positioning step was repeated for every time interval to give the complete OSEC for the day. Based on the OSEC plot for continuous 24 h operation, the largest value of the storage (S) can be identified and set as the storage capacity of the system. Fig. 2 shows the complete OSEC during start up for the Illustrative Case Study data.

The required outsourced electricity (deficits) and the power storage (surpluses) allocation at each time interval was observed. The period (peak or off-peak hours) of when the storage or outsourced electricity occurs was identified in order to plan an effective shifting strategy. The time intervals between 8 and 22 h are defined by Tenaga Nasional Berhad [15] as the peak hours. The time outside of the peak hours is where the off-peak periods take place. It should be noted that in Malaysia, the peak-off-peak electricity pricing are only charged to the industrial sectors. Since the electricity demands in industries are usually a fixed requirement, the proposed peak-off-peak load shifting approach is applicable to a limited number of industries or operations e.g. water pump in batch processes. Loads that have process interconnections or that are involved in a continuous process chain cannot be controlled independently. However, the interlocked processes can alternatively be shifted together if required. Potential industrial sectors that can implement load shifting strategy includes paper mill, food manufacturing and chemical plant [16].

The OSEC plot for start-up (see Fig. 2) shows that there are two instances where the outsourced electricity (O) is needed. 200 kWh of outsourced electricity is required between time intervals 6 and 8 h (off-peak period). Between time intervals 8 and 12 h (peak period) 2400 kWh is needed. The maximum storage capacity (S) of 2100 kWh occurs between time intervals 18 and 24 h, and 1500 kWh of electricity is also stored during peak hours (between 12 and 18 h).

Table 1
Limiting power sources and demands for the Illustrative Case Study [11].

No.	Power type	Description	Time, h		Power rating, kW
			From	To	
S1	Source	Solar	8	18	500
S2	Source	Wind	0	12	400
S3	Source	Biomass	12	24	600
D1	Demand	Appliance 1 (flexible)	6	12	300
D2	Demand	Appliance 2 (fixed)	8	18	350
D3	Demand	Appliance 3 (flexible)	8	12	500
D4	Demand	Appliance 4 (fixed)	0	12	350
D5	Demand	Appliance 5 (fixed)	12	24	500